# LAG–LEAD CORRELATIONS OF BAROMETRIC PRESSURE AND BIOLOGICAL ACTIVITY [1, 2]

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It has been known for many years that numerous kinds of organisms representing most of the major divisions of living things exhibit under constant conditions overt cyclic fluctuations of solar-day frequency of one or more of their processes. Less well known is the fact that at least a few organisms which live in the intertidal regions of the oceans have similarly clear cycles of tidal frequency. These rhythms appear to be expressions of a biological-clock system upon which the organism normally relies importantly in the adaptive regulation of its physiological behavior in its rhythmic external environment. In the past few years it has been firmly established that the frequencies of these cycles are independent of temperature over a wide temperature range, a characteristic which is, of course, an essential one if these cycles were to have practical adaptive value in the normal environment with its substantial fluctuations in temperature from hour to hour and day to day. Particularly within the past two years it has become more and more evident that all animals and plants have average solar-day and lunar-day fluctuations and that in the maintenance of these cycles, the organisms are receiving stimuli of some character from the fluctuating external physical environment even under conditions generally considered to be constant.

Evidence for an influence of a fluctuating external factor affecting the organisms even under "constant conditions" has come from both 1) highly significant correlations between hourly rates of metabolism in several organisms and concurrent hourly barometric pressure changes, and 2) remarkable similarities in the forms of day-to-day changes in mean rates of metabolism for the whole day, or specific parts of a day, and the forms of the day-to-day large climatic changes in the mean daily barometric pressures (approximated by the pressure for any arbitrarily selected, restricted, time of day). The day-to-day drifting of mean barometric pressures in a temperate-zone area appears superficially to be random, with every given period a month or so long, exhibiting its own specific pattern. Despite this, the forms of the day-by-day fluctuations in rates of metabolism or certain other biological phenomena of a number of species of organisms have appeared to be rather similar, either in a direct relationship or an inverse one, to the concurrent fluctuations in mean daily pressures. This has been found true to such an extent

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as to seem more than fortuitous, though there is no generally acceptable test for significance of correlations of such time series.

For many years relationship between barometric pressure and human physiology has been believed to exist. As a result of the prevalence of such a view during the first half of the last century Vivenot (1860) performed what he considered a crucial experiment to test this view. He constructed an air-tight chamber within which an experimenter could study pulse and respiration rates in subjects while the pressure within the chamber was experimentally altered. With this he found no evidence that small pressure changes had any influence upon the individual. A few years later, Lombard (1887) described striking similarities between fluctuations in the strength of the normal knee-jerk and concurrent fluctuations in external barometric pressure and temperature. The correlation was positive with pressure and negative with temperature. Later, the same investigator (Lombard, 1892) in more extensive studies reported a correlation between the rate of fatigue for voluntary contraction of the flexor muscle of the second finger and barometric pressure. With rising pressure there was increased capacity for work and with falling, decreased. The biological phenomenon retained its correlation with both the regular daily tidal and the irregular climatic pressure changes. Furthermore, pressure changes experimentally obtained by ascending and descending a mountain yielded quite comparable correlations.

Some experiments with spontaneous activity of other mammals yielded comparable apparent relationships to barometric pressure changes. Hodge (1897), studying the spontaneous running of two dogs through the application of special pedometers to their collars, found a correlation between the mean daily activities of the two dogs with respect to one another and to the concurrent mean daily barometric pressure. With the latter the correlation was positive over the two-month period of study. The correlation with pressure was extensively confirmed by Stewart (1898) employing rats and certain other mammals, in activity recorders. Gray rats exhibited a negative correlation with pressure over the 70-day period of his study. White rats, for a 30-day period included within the previous study period, showed a positive correlation with pressure. Stewart postulated, on the evidence at hand, that wild mammals displayed a negative, and domesticated animals a positive, correlation with pressure.

A widespread occurrence of a correlation between barometric pressure changes and biological activities was found by Brown, Freeland and Ralph (1955) and Brown, Webb, Bennett and Sandeen (1955) who were investigating fluctuations in $O_2$-consumption in potatoes, carrots, seaweed, fiddler crabs, and salamanders. All of these organisms showed correlations highly significantly different from zero between the hourly rates of $O_2$-consumption and the concurrent rate and direction of barometric pressure change. Later, Brown, Bennett, Webb and Ralph (1956) found correlations between the spontaneous opening of oysters and quahogs, and barometric pressure changes. In these recent studies it was strongly suggested by inspection of the data, however, that in paralleling the patterns of fluctuations, the organisms were actually leading the barometric pressure changes by more than a day.

One purpose of this report is to describe results from a simple statistical analysis of all the results on this score obtained in our laboratories between March 1, 1954 and June 9, 1955. These point conclusively to an ability of a wide variety of living

TABLE I

| Organism and place | Dates (inclusive) | Correlation times Organism/Bar. pressure | $r$ |
|---|---|---|---|
| *Fucus*[1] Woods, Hole, Mass. | July 28–Aug. 2 } 1954<br>Aug. 21–29 } | day $n$ / $n+2$ (5–7 A.M.) (5–7 A.M.) | −0.476±0.200 |
| | Aug. 3–20, 1954 | day $n$ / $n+2$ (5–7 A.M.) (5–7 A.M.) | +0.507±0.176 |
| *Ostrea* (10° C.)[2] Evanston, Ill. | Mar. 1–April 13, 1954 | day $n$ / $n+1$ (av. daily) (av. daily) | +0.411±0.125 |
| *Ostrea*[3] | June 18–July 28, 1954 | day $n$ / $n+2$ (av. daily) (av. daily) | +0.383±0.139 |
| | July 29–Aug. 27, 1954 | | −0.658±0.104* |
| *Rattus*[5] | Nov 16–Dec. 3 } 1954<br>Feb. 2–Mar. 13 } 1955 | day $n$ / $n+7$ (noon) (noon) | +0.598±0.068* |
| | Dec. 5–Feb. 1, 1954–55 | day $n$ / $n+7$ (noon) (noon) | −0.362±0.113 |
| *Solanum*[1] Evanston, Ill. | May 12–June 9, 1954 | day $n$ / $n+1$ | −0.650±0.110* |
| *Solanum*[6] Evanston, Ill. (5 groups) | April 1–June 8, 1955 | day $n$ / $n+2$ (5–7 P.M.) (5–7 P.M.) | +0.266±0.071 |
| *Triturus*[4] Evanston, Ill. | May 12–June 9, 1954 | day $n$ / $n+2$ (5–7 P.M.) (5–7 P.M.) | −0.842±0.059* |
| *Uca pugilator*[4] Woods Hole, Mass. | June 20–July 20, 1954 | day $n$ / $n+2$ (5–7 A.M.) (5–7 A.M.) | −0.472±0.144 |
| | July 21–Aug. 27, 1954 | day $n$ / $n+2$ (5–7 A.M.) (5–7 A.M.) | +0.595±0.104* |
| *Uca pugnax*[4] Woods Hole, Mass. | June 18–Aug. 29, 1954 | day $n$ / $n+2$ (5–7 P.M.) (5–7 P.M.) | −0.423±0.100 |
| *Venus*[3] Woods Hole, Mass. | June 18–Aug. 29, 1954 | day $n$ / $n+2$ (av. daily) (5–7 A.M.) | −0.446±0.096 |

[1] Brown, Freeland and Ralph (1955).
[2] Brown (1954).
[3] Brown, Bennett, Webb and Ralph (1956).
[4] Brown, Webb, Bennett and Sandeen (1955).
[5] Brown, Shriner and Ralph (1956).
[6] Brown (1957).
* Conventionally determined standard errors for such large values of $r$ do not provide true measures of probabilities.

things, ranging from lower to higher plants and from lower to higher animals, to show a lead correlation with barometric pressure changes by one to seven days (usually two). The only organism studied in our laboratory during this period which was not included in this report is the carrot, which was omitted, not because of any lack of similar type of correlation, but rather because there were some known injury effects on the $O_2$-consumption during part of the single-month period of study.

The organisms, the times of study, and the coefficients of correlation obtained in 703 organism-days are given in Table I. These are all correlations of three-day moving means except for the potato in 1955, in which daily mean values of $O_2$-consumption were correlated with three-day sliding averages of barometric pressure. Indicated in footnotes are the references to the publication of the results obtained with these species. In these publications it had not occurred to the authors to make this type of analysis, and furthermore, due to the extraordinary nature of the conclusions, it is to be doubted that a single demonstration of the phenomenon of a lead correlation, even though shown to be statistically significant (assuming random fluctuation in the organism), would have been credited by most physiologists.

All of the results were obtained in conditions of constant, continuous low illumination of the order of 1 ft. c. or less, except with the white rat, *Rattus,* for which two periods of continuous darkness, totalling 43 days, were included in the data. The conditions of the experiments with the brown alga, *Fucus,* two species of fiddler crabs, *Uca pugnax* and *Uca pugilator,* the salamander, *Triturus* and the potato, *Solanum* included also very precisely regulated constant temperature, and, in addition, for *Solanum* in 1955, constant pressure through the use of a barostat.

The biological process studied was the rate of $O_2$-consumption in *Fucus, Uca pugnax* and *Uca pugilator, Triturus* and *Solanum.* It was the average daily minutes open per hour for both the oyster, *Ostrea* and the quahog, *Venus;* it was the total distance spontaneously run per day in the case of *Rattus.*

To determine when the correlation would be highest, whether with the same day (day $n$) of barometric pressure, the following day (day $n+1$), the second day after (day $n+2$), or some earlier or later one, tracings of the fluctuations of the physiological process and of barometric pressure were superimposed and inspected in various temporal relationships. In the vast majority of cases, there was clearly only one relationship which promised high correlation with an obviously rapid drop towards no correlation with either greater or less displacement and no other relationship with nearly as high a correlation could be seen by such inspection over the rest of the period. In two cases, *Triturus* and *Solanum,* it was not evident from inspection, whether the correlation would be best with day $n+1$, $n+2$, or day $n+3$. In these cases, coefficients were determined for all three times and the highest one was selected; it was obvious, however, there was no other relationship with these species in which the correlation would be as high or significant.

The change in sign of the correlation from time to time seems clearly to be a biological contribution, probably to be compared superficially with the well-known changes of sign frequently observed in animal orientation. The sign change appears to occur abruptly and cleanly; the cause of the change is still unknown. It is known, however, that in all those cases examined in which the sign of correlation changed, there was concurrently a transformation of the form of the mean daily and lunar-day cycles to essentially their mirror images.

For all the periods the correlations ranged in size from 0.266 to 0.842. All were significantly different from zero by ordinary tests for correlations. Both the − 0.362 for *Rattus* and the 0.383 for *Ostrea* appeared to include one or two very brief periods of change of sign in the relationship. The potatoes in 1955, judging by periodic inversions of their solar-day cycles, appeared to be changing the sign of their correlation from time to time, and probably hence the lowest, though quite real, correlation.

The great majority of the correlations centered on day $n + 2$ of barometric pressure. *Solanum* in 1954 and *Ostrea* at 10° C., centered on day $n + 1$. The potato in 1955 gave almost the same correlation for $n + 2$ and $n + 3$. The most surprising result, on the basis of hypotheses available to account for this phenomenon, was that *Rattus* showed by far its highest correlation with day $n + 7$. The coefficient would have risen from $0.598 \pm 0.088$ to $0.668 \pm 0.07$ by the justifiable statistical procedure of eliminating from consideration the transitional values, those of Dec. 1–3 and Feb. 2, which were seen clearly to contribute naturally to neither series.

Since there appeared to be no test for the significance of correlations between two time series that would be acceptable to all statisticians, further experiments were performed to attempt to demonstrate the reproducibility of the phenomenon. The first of these involved a four-month study of potatoes in Evanston, Illinois. Small cores of potatoes bearing eyes were obtained by means of a large cork-borer, and one was placed in each of 20 respirometer vessels (Brown, 1954). Four respirometer vessels upon a single recording system were sealed in each of five barostats on Feb. 1, 1956. During a three-month period, the respirometers were opened for about 15 minutes once every two to six days, to refill the $O_2$-reservoirs and replace the $CO_2$-absorbent. Very rarely a potato was replaced with a new one during this period. On the first of May, a completely new lot of potatoes replaced the old, and the observations were continued through May 31. During this study the potatoes were maintained in constant conditions of temperature (19.5° C.), of light ($< 0.5$ ft. c.), and of all other factors known to influence organisms. The respirometers were kept under a constant reduced pressure of 28.50 inches Hg. Approximately 56,000 organism-hours of $O_2$-consumption were obtained.

Inspection of three-day moving means of the mean daily barometric pressure for the four-month period, and comparison of weighted (1:2:3:2:1) five-day moving means of the 4–7 P.M. deviation in rate of $O_2$-consumption from the daily mean, gave clear suggestion that just as with the potatoes in the 1954 and the 1955 experiments, there was a lag correlation of barometric pressure on $O_2$-consumption by about two days. A scatterplot of the relationship between the barometric pressure of day $n + 2$ and $O_2$-consumption on day $n$ is seen in Figure 1. This yielded a correlation coefficient of $0.339 \pm 0.0835$, a value highly significantly different from zero.

Figure 1, B, illustrates the various values of $r$ obtained in various lag-lead relationships between the two phenomena, *i.e.,* for $O_2$-consumption of day $n$ correlated with barometric pressure in various temporal relations from day $n - 30$ to day $n + 15$, a 45-day span. In this instance not only was a correlation centered

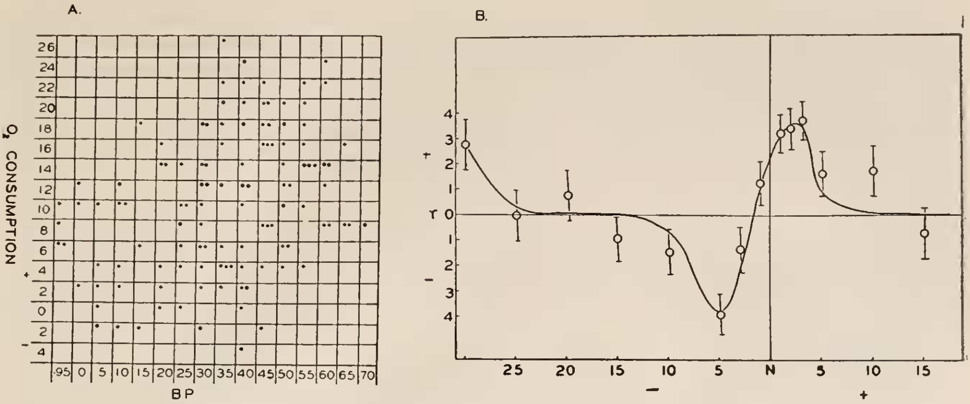


FIGURE 1. A. Scatterplot of the relation between the mean barometric pressure on day $n+2$ and the 5–6–7 P.M. deviation from the daily mean of $O_2$-consumption of the potato on day $n$. B. Coefficients of correlation (ordinate) between the 5–6–7 P.M. deviation in $O_2$-consumption from the daily mean on day $n$ and the mean barometric pressure on various days from $n-30$ to $n+15$ (abscissa).

on day $n+2$, but a correlation was also found with barometric pressure, day $n-5$.

A second attempt was made in 1956 to confirm an organismic lead-correlation of metabolism on barometric pressure. This one was performed in Woods Hole, Mass., between June 16 and August 1. These observations were made upon fiddler crabs, whose $O_2$-consumption was measured under constant conditions including pressure in the same type of apparatus as that used for the potatoes. In this study of the fiddler crab, the temperature was similarly very constant but at a higher

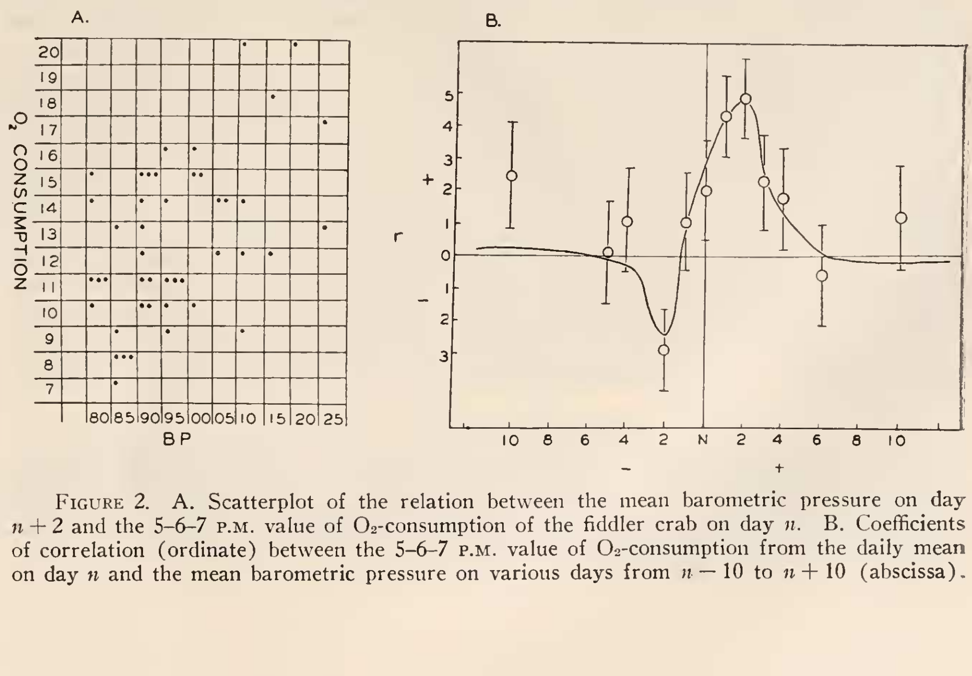


FIGURE 2. A. Scatterplot of the relation between the mean barometric pressure on day $n+2$ and the 5–6–7 P.M. value of $O_2$-consumption of the fiddler crab on day $n$. B. Coefficients of correlation (ordinate) between the 5–6–7 P.M. value of $O_2$-consumption from the daily mean on day $n$ and the mean barometric pressure on various days from $n-10$ to $n+10$ (abscissa).

value, near 24° C. In this analysis, as for the experiments performed in 1954 and 1955, the actual rates of $O_2$-consumption at the 4–7 P.M. period were used. The scatterplot relationship between respiration on day $n$ and barometric pressure on day $n + 2$ is shown in Figure 2, A. This yielded a coefficient of $0.49 \pm 0.12$, remarkably close, coincidentally, to the mean of all the values obtained in 1954 and 1955 (0.5). In Figure 2, B, are depicted the values for r together with their deviations for this and other lag-lead correlations between day $n$ of $O_2$-consumption and day $n - 10$ to $n + 10$ for pressure. The only real correlations in the series are for days $n + 1$ and $n + 2$, with the latter being the more highly significant. In these correlations with the crabs three-day moving means were used for both pressure and metabolism.

These two series of experiments performed in 1956 would appear to confirm in a striking manner the conclusions reached in the earlier studies.[3]

The explanation of the phenomenon considered here seems from a general standpoint to be quite evident. Since the organisms cannot be determining the barometric pressure changes which are to occur, the organisms must be responding to some physical factors and their fluctuations which themselves exhibit a lead-correlation on barometric pressure. The potatoes in 1955 and the potatoes and crabs in 1956 remained in each case in barostats at 28.50 inches Hg from one to three months, the barostats opened only for about 15 minutes once every two to six days, and hence, the lead correlation cannot be due to any special responses to current rates of change in pressure itself. Since organisms have been shown to possess fluctuations in metabolic rates correlated with the rates and directions of barometric pressure change and especially since 27-day cycles have been found, it appears suggestive that the organism may be able to respond directly to fluctuations in the intensity of some high energy radiation or of some other physical factor with radiation-correlated fluctuation.

It is futile at the present time to do much speculating as to the external forces involved and the manners in which fluctuations in them may interact with the now established solar-day and lunar-day clocks and average cycles within organisms. This is now being investigated. It may be shown eventually that the phenomenon described in this report depends in some manner on the possession by both the organisms and the atmosphere of a solar-day and lunar-day cyclicity, and the interaction of these with some less orderly cosmic factor to which both the organism and atmosphere can react in an oscillatory fashion. But irrespective of the detailed mechanism, correlations of the order of magnitude described here (nearly 0.50 as the average degree of correlation for eight species of animals and plants over about 850 days), and tending very strongly to be centered on day $n + 2$, especially since they cannot be correlations with an actual causative force, are to be viewed as extraordinary. They force one to conclude that the living organism is clearly responsive in an orderly way to forces not hitherto seriously considered by biologists to possess any influence.

[3] Since the manuscript was completed, a further study of the potato during October, November and December, 1956 also yielded a lead correlation in which the highest correlation ($-0.400 \pm 0.089$) was similarly found with the mean barometric pressure of day $n + 2$, rapidly falling on days $n + 1$ and $n + 3$ to $-0.307 \pm 0.094$ and $-0.328 \pm 0.093$, respectively, and on days $n$ and $n + 4$ to a value not significantly different from zero. From inspection there was no other lag or lead relationship in which a significant correlation existed.

For the biologist who is attempting to account for the remarkable capacity of organisms to measure off with great precision under so-called "constant conditions," temperature-independent cycles of the frequencies of natural external cosmic events, it becomes highly important to know whether the conditions are truly constant for the organism, and if not, what is the actual character of the fluctuations in the effective external factor or factors.

## Summary

1. Eight species of living things, ranging from lower to higher plants and lower to higher animals, in studies over a three-year period and including approximately 850 species-days have exhibited without exception a statistically significant lead-correlation on barometric pressure with an over-all mean coefficient of about 0.5.

2. The correlation involved sometimes only the 5–6–7 A.M., sometimes only the 5–6–7 P.M., and other times the mean daily rates of $O_2$-consumption.

3. The sign of the correlation was sometimes positive and other times negative. Sign changes, when they occurred during a single period of study were abrupt, and correlated with a 180°-shift in the phase relationships of the concurrent mean solar-day cycles.

4. In twelve periods of study, ranging from one to four months each, the correlation in nine cases centered on day $n + 2$ of barometric pressure. In two cases it centered on day $n + 1$ and in one, on day $n + 7$.

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